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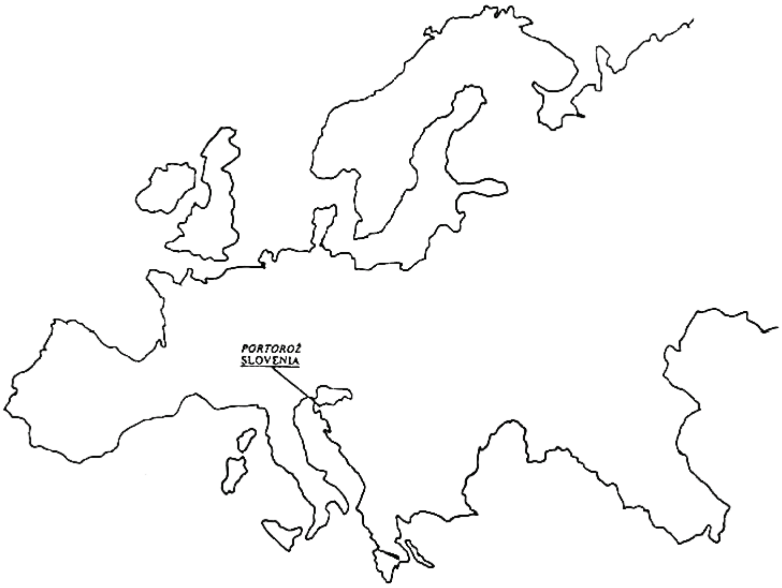

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FLOW AND TRANSPORT IN FRACTURED MEDIA AS A BASIS FOR POLLUTION CONTROL

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ABSTRACT

To trace the pollutant propagation from the pollution source downstream to a well, spring or another point of interest within the aquifer the following information must be available: 1) type of pollutant, location and area of pollutant imission, pollutant concentration at the imission point (or area), distance of the imission point (or area) to the point of interest, 2) hydrogeologic characteristics of the aquifer, 3) flow characteristics: flux, velocity and direction, 4) transport and retardation phenomena involved, 5) pollutant concentration at the point of interest

By its objective, the groundwater pollution protection may be regarded as a general environmental protection, or as a water resources protection. In the first case is the pollution control, generally dealing with extremely toxic, noxious or radioactive pollutants, trying to prevent any leaks from pollution source or to contain the pollution within a limited rock or aquifer volume. To achieve this goal, the velocity and the extent of pollutant spreading is being closely controlled and, if necessary, pollution containment measures applied. In the second case, the pollution control is a combination of protection, prevention and intervention measures designed to maintain the supplied water quality within the prescribed standards. As a general protection measure, protection zones are being prescribed around the water catchments.

Three types of conceptually different models are used to model the fluid flow and mass transport within the fractured and/or karstified rocks: 1) Equivalent continuum model, 2) Discrete flow models and 3) Double porosity models.

To control the pollution in fractured and in karstified rocks by mathematical modelling, the nature of these media and of the corresponding flow and mass transport must be adequately described. Quite often, especially with fractured and karstified rocks, this cannot be done either due to the insufficient understanding and formulation of the involved phenomena, or due to the lack of adequate data. The lack of adequate data will always be a part of the problems of lesser economic or social importance. Cases will always emerge, where conceptual models and practical engineering approaches will substitute the mathematical modelling and where the intuitive solutions will cope with the lack of data.

At the current state of pollution control of water resources, the protection zones represent the main legal protective and preventive measure. This zones have rational background based on the expected Travel times of the pollutant from the pollution source towards a given resource. Whereas for the aquifers with intergranular porosity these zones are generally quantitatively defined, it is not so for the protection zones in fractured and, especially, karstified aquifers. Here, most of the protection zone design is still done on the intuitive and qualitative bases. The general knowledge provided by the corresponding research of the flow and transport phenomena will help to improve this type of solutions and actions. Thus, the qualitative approach will be confined to the cases of lesser environmental threat and economic importance.

INTRODUCTION

Water quality is of great interest in any development or management of water resources. With the increased demand for water and with the intensification of its use, it is becoming the limiting factor in the development and use of water resources. Groundwater pollution control, involving pollution reduction and prevention and antipollution protection can be regarded as a general environmental protection, or as a water resources protection. In the first case, groundwater with little or no water resource value (in semi-pervious rock massifs, poor aquifers or degraded parts of more important aquifers) is being protected as a potential transmitter of pollution to the other groundwater and surface water bodies and to the other environment. In the second, protection refers to the aquifers, representing actual or potential water resources, and to the water supply catchments.

Hydraulic conductivity of fractured and karstified rocks (or fractured media), depends primarily on the fissure, fracture and channel (karst channel) network characteristics. For most rocks it varies over several orders of magnitude. To back the pollution control in fractured and in karstified rocks by mathematical modelling, the nature of these media and of the corresponding flow and mass transport must be adequately described. With fractured and karstified rocks, this cannot be done often either due to the insufficient understanding and formulation of the involved phenomena, or due to the lack of the adequate data.

At the current state of water resources pollution control, the protection zones represent the main legal protective and preventive measure. Their rational background is the expected pollutant travel times towards a resource. Yet, most of the protection zones are still designed in karst aquifers on the intuitive and qualitative bases. This has to be improved.

POLLUTION AND WATER QUALITY

Water quality is of great interest in any development or management of water resources. With the increased demand for water and with the intensification of its use, it is becoming the limiting factor in the development and use of water resources.

Water quality is a term relating to the physical, chemical and biological characteristics of water (Pfannkuch,1990). Most materials can be dissolved or suspended in water, which can also contain various amounts of (heat or radiation) energy. Water quality can therefore be defined in terms of hundreds of parameters, making its determination very costly if not complicated.

The use of water is deciding the relative importance of water constituents and physical characteristics. Water quality can be defined relative to its use and that is what is being done in everyday life. Separate water quality standards were defined for drinking water, for irrigation water and for various industrial and recreational water uses.

Pollution is the contamination of the environment - of groundwater - with undesirable, harmful or obnoxious substances (Pfannkuch,1990). Yet, behind this clear definition, two ideas of pollution have been advanced.

According to the first idea (Fried,1975), pollution is any change in water quality (composition) that is deteriorating or preventing its use, despite the origin of its constituents and the processes involved. *Pollutant* is in the sense of this definition any directly or indirectly detectable undesirable substance or property of water. According to the second idea (Filipović&Vujasinović,1982), pollution is only the deterioration of water quality relative to its initial, by man's activity undisturbed state. Despite the concept involved, when speaking of 'water pollution' rather than of 'water quality' we generally have in mind the water quality deterioration to the point of being hazardous to the consumer (Bear&Verruijt,1987).

To define the state of pollution, the generally accepted and applied qualifiers are: *critical pollution* (Veselič,1984), denoting the dangerous or unacceptable level of a given pollutant, and the *state of pollution*, denoting the actual level of a given pollutant. Other qualifiers of pollution have been proposed (Veselič,1984): *measure of pollution* denoting the relative deterioration of a pollution parameter (constituent, indicator, property) due to a certain pollution source. Practical experience has shown that the *degree of pollution* should be defined as a relative measure of the state of pollution of a given pollutant (quotient of its state of pollution level to its critical pollution level) enabling the authorities to react legally before its critical pollution level is reached. An interesting approach to the estimating of critical pollution is the definition of the *critical integral pollution* (-Filipović&Vujasinović, 1982) as the sum of the individual degrees of pollution of all toxic compounds, which has to remain below unity: $\sum(x_i/X_i) < 1$ (with x_i and X_i denoting the state of pollution and the critical pollution of the i-th compound respectively), if the water is to be used for drinking purposes.

The following types of pollution can be defined regarding its sources (Bear& Verruijt,1987):
- *Environmental*, resulting from the environment through which the water flows, or from adjacent poor water quality aquifers or water bodies due to a man made or naturally caused disturbance of the original equilibrium state (i.e. acid water, salt water and sea water intrusions, etc.).
- *Domestic*, resulting from accidental or planned, but poorly engineered releases from septic tanks, sewage systems and sanitary landfills and accidental spills from

house heating combustion oil tanks (i.e. breaking of sewers, artificial recharge of aquifers by poorly treated sewage water, percolation water from landfills, etc.). Biological contaminants (bacteria, viruses) are resulting from this source.
- *Industrial*, resulting from accidental or planned, but poorly engineered releases from industrial processes, from transport and from industrial waste (i.e., oil spills, process and sewage water releases, percolation water from landfills, etc.). Industrial pollution resulting from industrial waste is particularly dangerous (heavy metals, highly toxic or radioactive compounds, etc.).
- *Agricultural*, resulting from farming and land cultivation and due to rain and irrigation water replenishing the underlying phreatic aquifers (i.e. manure and other fertilizers spreading, plant and crop treatment, reclaimed sewage water irrigation, etc.). Organic and inorganic contaminants (pesticides, herbicides, nitrates, etc.) and biologic contaminants are resulting from this source.

In cases where sewage disposal systems serve both industrial and residential purposes, industrial and domestic waste cannot be separated. The same is true for village areas, where agricultural pollution from farms cannot be separated from the domestic one and is generally considered as domestic pollution.

When traced back to its source, other important aspects of pollution are the input area and the input duration. With respect to the input area, pollution can be defined (Janež,1988) as either *concentrated (point source) pollution* or *disperse pollution*. With respect to its duration, it can be either *single pollution*, or *repeated*, *periodic*, *seasonal*, or *permanent* one. Agricultural pollution, as defined by Bear and Verruijt (1987), is by its input a typical disperse pollution and a seasonal one. Inversely, domestic and industrial often result from point sources.

According to its source and to its nature, the pollution can either be *foreseeable* and anticipated or *unforeseeable* and unanticipated (Janež,1988). This aspect is important when considering pollution control.

Whatever its source, but with respect to the temporal stability of the involved pollutants, the pollution can either be *short term pollution*, or *long term pollution*, or even *permanent* one.

Finally, *polluter* is the one who is polluting and is therefore the source and the responsible of pollution.

PRINCIPLES OF POLLUTION CONTROL

Pollution control denotes anti pollution campaigning, involving its reduction and prevention and anti pollution protection - in our case of groundwater. All measures taken with this respect are termed *pollution abatement*. Pollution abatement therefore starts at the actual or potential pollution source as a set of measures preventing the mere occurrence of pollution. *Pollution prevention*, denoting conservancy, conservation and water quality management (Pfannkuch, 1990) is therefore a part of the pollution control.

Once water pollution occurred, as it unfortunately too often does, its spreading from the source must be regarded as a transport of mass or (heat or radiation) energy through the porous medium retaining subterranean water. The 'mass' of some substance (similar is for the energy) is being moved by water through the porous medium, let it be unsaturated or saturated. The mechanisms affecting the pollutant transport in such a medium are advective, dispersive and diffusive fluxes, solid-fluid interactions, various chemical reactions and decay phenomena, which can be regarded as source-sink phenomena for the pollutant (Bear&Verruijt,1987). And as far as the biological pollution is considered, the above list of mechanisms has to be enlarged by the biological processes, defining the endurance of a given species or pollutant within the groundwater environment.

Pollutant propagation within the aquifer from the pollution source downstream to a well, spring or another point of interest can be traced if the following information is being available:

- type of pollutant, location (or area) of pollutant imission, pollutant concentration at the imission point (or area), distance of the imission point (or area) to the point of interest,
- hydrogeologic characteristics of the aquifer,
- flow characteristics: flux, velocity and direction,
- transport and retardation phenomena involved,
- pollutant concentration at the point of interest

At the pollution source, a pollutant imission into the groundwater may be direct or indirect. In the first case, a pollutant is injected directly into the saturated zone of the aquifer. In the second, it is disposed within the aquifer's unsaturated zone, within the adjacent aquitards (low permeability rock bodies) or to the land surface above the aquifer. With indirect pollutant disposal, a concentrated pollution inflow affects the aquifer much faster than a disperse one. Again, with the indirect pollutant imission, surface disposal, activating the soil's filtration and biological decay potentials, retains and reduces pollutant propagation additionally.

To control the water pollution once it occurred from a pollution source, one has to be able to simulate the processes that govern the pollution transfer at least qualitatively if not quantitatively. A throughout quantitative simulation of the pollutant transfer is the desired ultimate tool of a perfect pollution control. The resulting computing models should enable the engineer and planner to predict the distribution of pollutants within an aquifer as a function of its rock and flow characteristics, of the pollutants' input area and of the time elapsed between the pollutant imission and the observed distribution period.

The importance of the problem and the corresponding quality and quantity of the available information determine whether the resulting approach must remain only qualitative or semiquantitative or has to be quantitative (involving modelling).

By its objective, the groundwater pollution protection may be regarded as a general environmental protection, or as a water resources protection. In the first case, groundwater in semi-pervious rock massifs and poor aquifers or degraded parts of more important aquifers, all with little or no water resource value, is being protected as potential transmitter of pollution to the other groundwater and surface water bodies and to the environment in general. In the second, protection refers to the aquifers, recognized as actual or potential water resources, and to the water supply catchments.

Pollution control in the first case, generally dealing with extremely toxic, noxious or radioactive pollutants, is trying to prevent any leaks from pollution source or to contain the pollution within a limited rock or aquifer volume. To achieve this goal, the velocity and the extent of pollutant spreading are being closely controlled and, if necessary, pollution containment measures applied.

Pollution control in the second case is a combination of protection, prevention and intervention measures designed to maintain the supplied water quality within the prescribed standards.

As a general protection measure, protection zones are being prescribed around the water catchments. From the protection aspect, we have to distinguish between the following areas:

a) areas, where potential pollution cannot be prevented from entering the water supply system,
b) areas, where potential pollution cannot be prevented from entering the catchment area, but can be, within a given intervention period, prevented from entering the water supply system,
c) areas, where potential pollution cannot be prevented from entering the aquifer, but can be eventually prevented from entering the water catchment,
d) areas, where (within a given intervention period) potential pollution can be prevented from entering the aquifer.

The accepted intervention delays, the expected pollutant retention, decay and dilution and the expected groundwater flow velocities will decide the extent of protection zones. Standards, applied in different countries (Blau,1990:DVGW, Arbeitsblatt W 101/75 for Germany; BUS 1977/82 for Switzerland; Breznik,1976: ZSRSDP, Guidelines 3/4-1976 for Slovenia), are all determining:

1. *Zone of immediate protection*, corresponding to the area a) and covering 5-50 m around the water catchment and designed to prevent any pollutant imission; Slovenian guidelines prescribe a second immediate zone covering an area with 15-30 days upper inflow time limit,
2. *Zone of inner protection* or of strong sanitary regime, corresponding to the area b) and covering an area with upper inflow time limit sufficient for the elimination of pathogenic germs and hardly or non-degradable chemicals; German standards prescribe a time limit of 50 days, Slovene guidelines a time limit of 30-60 days. Swiss standards prescribe a minimum residence time limit of 10 day and a minimum extension limit of 100 m (Blau,1990); while evaluating the excess of the critical residence time over the 10 days' minimum t_{mc}, the effects of the unsaturated zone modifying time t_{mc} to t_c can be taken into account (Rehse,1977 in:Blau,1990) according to the formulas $dt = 100 - (x-5)J$ % and $t_c = t_{mc}(1+dt/100)$, where x denoting metric unsaturated thickness and J rock cleaning indexes (e.g. sandy gravel J=2.5, silty sand J=10).
3. *Zone of outer protection* or of loose sanitary regime, corresponding to the area c) and covering all the groundwater inflow area of a considered water catchment or all the extent of a protected water resource subject to direct rainfall or irrigation infiltration; no specific time limit is requested. According to Swiss practice (Blau,1990), it is generally designed to have twice the length of zone 2.
4. *Zone of restricted* protection, corresponding to the area d) and designed to cover all the area with direct rainfall infiltration directed towards the protected resource; protection area A of Swiss standards and zone of influence of Slovene standards.

To make the above protection zones operational, the appropriate pollution monitoring and intervention policy must become an integrated part of the pollution control system.

It is obvious from the definition of the protection zones, that neither these zones and the corresponding monitoring system nor any other pollution containment and control can be defined without considering the flow and transport of the pollutants through the aquifers and other water bearing rocks.

FRACTURED ROCKS AS POROUS MEDIA

Fractured rocks are constituted of blocks of solid rock or matrix, intersected by discontinuities. General aspect of the fractured rock is given in the Figure 1.

During the karstification process can rock's discontinuities, especially their intersections, evolve into karst channels. General aspect of the karstified rock, with the (solution) karst channel development following bedding planes and faults, can be seen from the Figure 2. Other channel forming processes may produce channels in the so-called pseudo-karst.

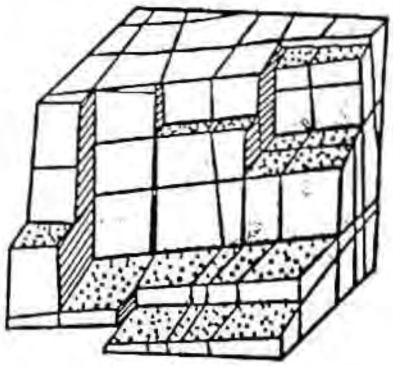

Figure 1 - View of a fractured rock mass (after Veselič,1995)

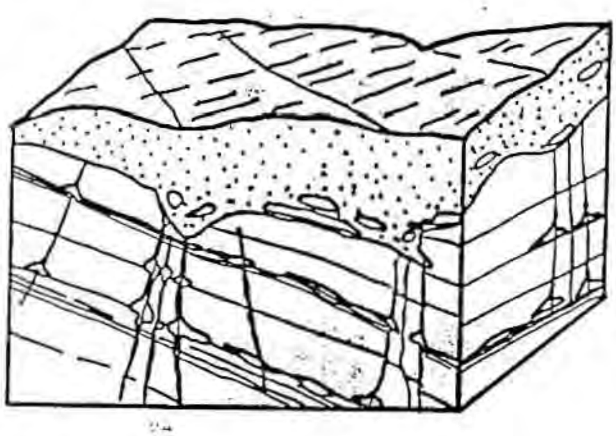

Figure 2 - Block diagram of a karstified rock with the karstification pattern (after Veselič,1995)

International Society of Rock Mechanics (ISRM) Suggested Methods for Quantitative Description of Discontinuities in Rock Masses [Brown,1881, Cheng-Haw-Lee&Farmer,1993) recommend the use of term discontinuity instead of other, generic terms for breaks in rock mass continuity. The term 'discontinuity' is regarded as the general term for any mechanical discontinuity with zero or low tensile strength in a rock mass and is used here in the sense of these recommendations.

Several sets of discontinuities can be defined within a rock mass if they are grouped by geometric and/or by generic criteria. This sets usually display some hierarchical order. Individual sets can be ranked according to the important parameters, which will in groundwater hydraulics generally be the water flow influencing parameters or the flow itself.

Geometrical criteria consider size, dip and spacing of discontinuities and their total width, opening, wall rugosity and percentage of fill. By genetic criteria we distinguish between bedding planes, stiliolyths, cleavage or schistosity planes, fractures or joints and faults. They are presented in the Table 1.

LENGTH			MAXIMUM OPENING		FRACTURE DENSITY		ORIENTATION	STUDY SCALE	STUDY APPROACH
microfractures	0.1Å	ionization at excitation		intra and inter granular fissures and cleavage			unoriented	sample	texture
	10 Å	crystalline incl. atoms							
	0.1µm	intracrystalline dislocations							
	10 µm	intergranular joints							
	1 mm	microfractures	1 µm	microfractures - schistosity foliation		fissured rock			
			0.1 mm						
macrofractures	1 dm	schistosity		macrofractures		broken rock	oriented	construction site	structure
						very dense			
	10 m	joints fractured zones	cm	joints bedding planes	5 cm	dense			
					30 cm	fairly dense			
	1 km	faults	dm	faults	1 m	low density			
					3 m	very low density			
				channels	10 m				
			m	karst channels	?	occasional			
adapted after Talobre (1967)			adapted after Farran & Thenoz (1965)		adapted after Deere (1968)				

Table 1 - Fissures, fractures and channels; genetic terms and characteristics (adapted after Louis,1974)

For hydraulic characterization of rock masses, Louis (1974) proposed 11 parameters: type of structural element, orientation, continuity, opening, nature of filling material, degree of void area, water inflows, decompression, spacing between elements, nature of fracture endings, roughness or angle of friction. Some of them are displayed on the Figure 3. It was shown by Louis and Pernot (Louis,1974) that the data from classical structural analysis have to be weighted according to the rank (N) of the class of fracture opening and continuity or fracture seepage with the following type formula: P(N) = 1 + opening(N) + continuity(N). It must be noted that the required information on fracture continuity can be obtained only from the walls of excavations.

Ten parameters are recommended by the already mentioned publication of ISRM (Brown,1981): orientation, spacing, persistence, roughness, wall strength, opening, filling, seepage, number of sets and block size (Cheh-Haw-Lee,1993). Seven of these correspond to Louis (1974) proposal and two characterize only the fractured rock mass.

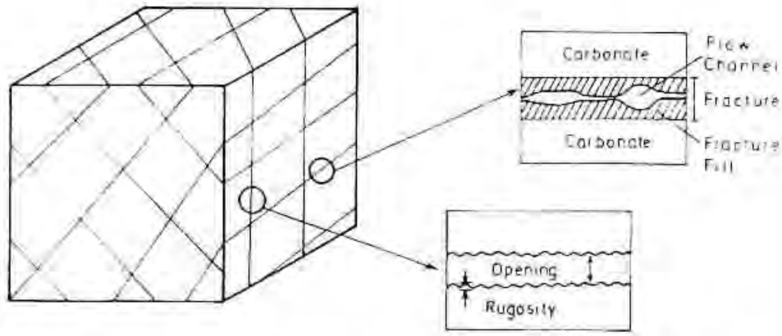

Figure 3 - Block diagram of fractured rock with display of hydraulically important fracture parameters

Recent studies in granites (Cacas&al.,1990) concentrate to define fracture density, mean length and other statistical parameters (standard deviation, etc.) of the individual fracture sets. For the individual sets, the fracture parameters distribution has been found lognormal.

Hole	Test section depth (m)	Rock	LU	K (m/s)	RMR	RQD	FI
KT1	55.00 - 60.00	granite	0.05	$5x10^{-9}$	III/II	76-100	12.0-0.7
	75.00 - 80.00	basalt	0.05	$5x10^{-9}$	III/II	64-100	9.3-1.3
	100.50 - 105.50	granite	0.06	$6x10^{-9}$	III/II	35-94	13.3-4.4
	126.00 - 131.00	granite	0.24	$2.4x10^{-8}$	(IV)III/II	12-100	11.4-2.7
TO1	49.40 - 53.90	tuff	0.02	$2x10^{-9}$	III/II	53-76	>20-3.9
	56.10 - 60.60	tuff	0.03	$3x10^{-9}$	II	56-100	9.2-4.0
	69.30 - 74.30	eutaxite	0.02	$2x10^{-9}$	II	67-100	8.6-1.1
	84.95 - 90.19	tuff	0.14	$1.4x10^{-8}$	II	50-100	5.4-0

Table 2 - Water injection test derived Lugeon and water conductivity values related to RMR, RQD and FI indexes (after Veselič, 1994)

The real problem in fractured rock characterization is the fact that only a few of these parameters can be determined with precision while most can only be estimated. Even with the engineering problems, where the data on fresh rock can be obtained from excavation or drilling this is a serious problem and other descriptive parameters (RMR - rock mass ratio, RQD - rock quality designation, FI - fracture index) are applied for the rock characterization. As shown from the Table 2, the correlations can be drawn between these parameters and rock hydraulic conductivity values, but they are not always very obvious.

With the regional groundwater flow problems are the fresh rock exposures and the appropriate drilling data much less available. Therefore, the data on the morphology of the discontinuities and on their seepage flow are generally missing. They tend to be substituted by other structural data, obtainable by detailed mapping. Here, the method developed by Eraso (1986), based on the detailed statistical structural analysis of the outcrop and other structural data has proven very successful in karst terrains as shown on the Figure 4.

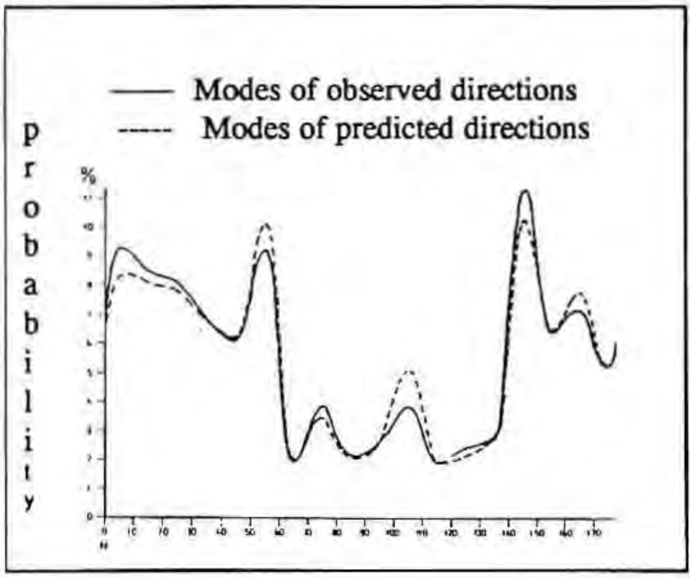

Figure 4 - Comparison between the observed and calculated directional frequencies of the active karst drainage channels in Libar, Spain (after Eraso,1986)

Porous media are inherently heterogeneous. The concept of the representative elementary volume (REV) was invented in order to describe the whole media as an infinite replication of this volume. The REV's size must assure that its volumetric averages are satisfactory estimates of all the relevant statistical parameters of the void space configuration (Bear&Verruijt,1987, Bear&Bachmat, 1986) of the represented porous media. This concept enabled a deterministic approach to such media.

REV relates only to a homogeneous porous medium. With the natural aquifers this may, due to their heterogeneity, require the definition of several REV, each one relating to the part of the aquifer or rock volume, which is both intrinsically homogeneous and characteristically different from the others.

Fractured and karstified rocks are made of blocks of solid rock, intersected by discontinuities, which may be locally developed into channels. Matrix, discontinuities and channels are all possessing a certain porosity. In most fractured and karstified rocks the fracture and channel porosity are hydraulically preponderant. However, the matrix porosity can not be neglected - especially when considering void volume, water storage or mass transport.

The heterogeneity of the fractured and karstified media, compared to that of the media with intergranular porosity, is very pronounced. The REV concept was extended also to these media as shown on the Figure 5 by the example of an outcrop of stratified dolomite with a pronounced cleavage (parallelepiped in reality), intersected by faults. As in a general case, several sets of discontinuities are present.

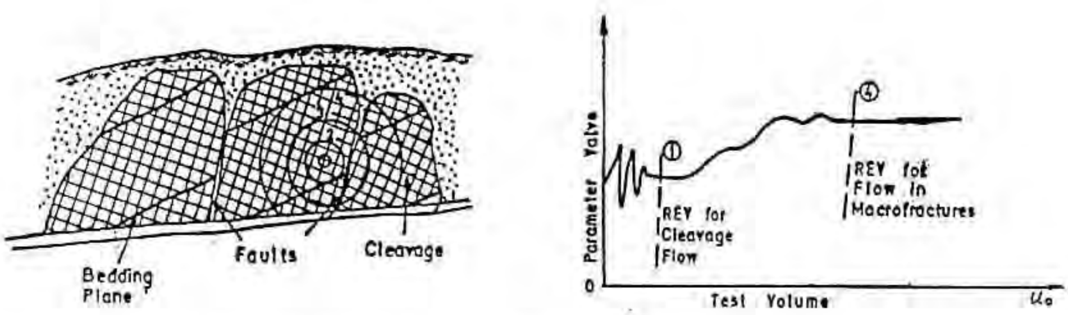

Figure 5 - Outcrop of a fractured dolomite and the corresponding Representative Elementary Volumes (after Veselič,1995)

From the corresponding diagram, it follows that one REV can be defined for the cleavage domain and another for a larger domain, where faults and bedding planes influence rock parameter values. This illustrates the double porosity concept, often used to model fissured and fractured or karstified aquifers (Reiss,1980). Generally, clear difference can be observed between the porosity of microfractures and that of macrofractures and channels. The former is often assimilated to the matrix porosity.

Total and effective porosities are generally much lower in fractured rocks than in the rocks with the intergranular porosity. Matrix porosity is a sum of intergranular and microfracture (fissure) porosities. The effective porosity sums up macrofracture and channel porosities. In the Table 3 are given some data on carbonate rocks (which underwent geosyncline burial and orogenesis and are representative post geosynclinal fractured and karstified rocks), on schists and sandstones from Slovenia and on granites and gneiss from Sweden.

Rock type	Rock age	Matrix porosity			Effective porosity
		Intergranular		Micro fracture	
		Mean	Range		
granite, gneiss				10^{-3}- 0.01	10^{-5}- 10^{-4}
schist, sandstone	P_2^2	-	-	10^{-4}- 0.05	< 0.02
limestone	T,J,K	0	-	0 - 0.02	< 0.01
dolomite	T_3^2, T_3^3	0.0055	0 - 0.1	0 - 0.06	< 0.02
dolomite	T_2^2	0.0033	0 - 0.05		
dolomite	T_2^1	0.0034			
dolomite	T_1^2	0.01	0 - 0.02		
dolomite	T_1^1	0.002	0 - 0.02		
dolomite	P_3	0.073	0-0.1		

Table 3 - Porosity data for fractured and karstified rocks
Source of data: granites&gneiss (Sweden) - Abelin&al., (1991a,b); intergranular (matrix) porosity of carbonate rocks (Slovenia) - Mlakar (1975), Ogorelec (1978, 1979) and Ogorelec&Orehek (1975), other data - personal unpublished reports

Matrix (microfracture) and effective porosities, dependant on the structural data, can be deduced from the later data according to the formula $n_e = \sum a_i D_i o_i$, where symbols signify: a - fracture opening in m, D - fracture density in m^{-1} (number per m), o - open (unfilled) fraction of the fraction and i - the i-th fraction set. However, it is better to deduce them from the on-site hydraulic tests. The effective porosities are generally within the 1 - 2 % range.

FLOW AND TRANSPORT IN FRACTURED MEDIA

Hydraulic conductivity distribution

Hydraulic conductivity of fractured and karstified rocks depends primarily on the fissure, fracture and karst channel network characteristics. For most rocks it varies over several orders of magnitude as shown on the Figure 6. To compare with the intergranular rocks, the data on clay were added.

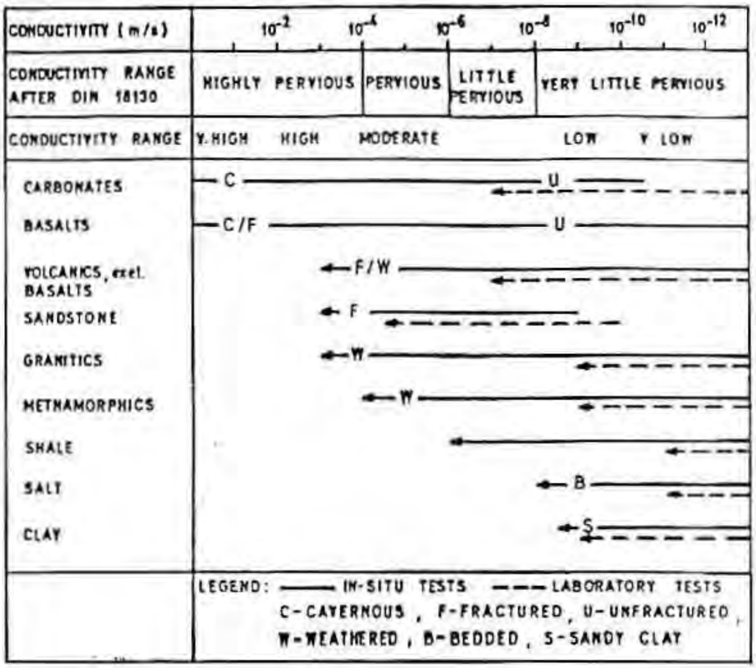

Figure 6 - Hydraulic conductivity of rocks; (after Veselič,1995)
Data by Cheng-Haw-Lee&Farmer (1993), Johnson (1967), Hölting (1989) and Veselič (unpublished reports)

As seen from the above differences between the laboratory and the field data, the laboratory tests generally do not provide representative information as they can not account for fracture and channel conductance. On-site tests are needed to obtain reliable results.

It has been found (Matheron,1967 in:Cacas&al.,1990, Gutjahr&al.,1978, Dagan,1982) that in a three-dimensional porous medium the global permeability value K for the parallel flow conditions lies between the geometric mean K_g and the arithmetic mean K_a of the local permeabilities with the first order approximation being $K = K_g(1+\sigma^2/6)$. In a homogenous and isotropic fractured medium, a series of local injection tests can thus be used to obtain the global permeability. In this way, in a granitic rock (Cacas&al.,1990) with a mean fracture length of 1 m and a mean fracture density of 7 fractures per m^3, a rock block with a 10 m edge has been found statistically representative of the local fracture network, while a REV size of at least 100 m was necessary to provide the mean rock permeability.

Even for the granitic rocks it was found (Cacas&al.,1990, Moreno&Neretnieks, 1993a), that the fluid flow within fractures was actually a channel flow. Moreno & Neretnieks report of a channel density of 1 channel per 20-200 m^2 of the cross-section area, which certainly requires even bigger REV to obtain the mean permeability value. From the Figure 7 it can be seen how extremely scale sensitive with this respect are the karstified carbonate rocks.

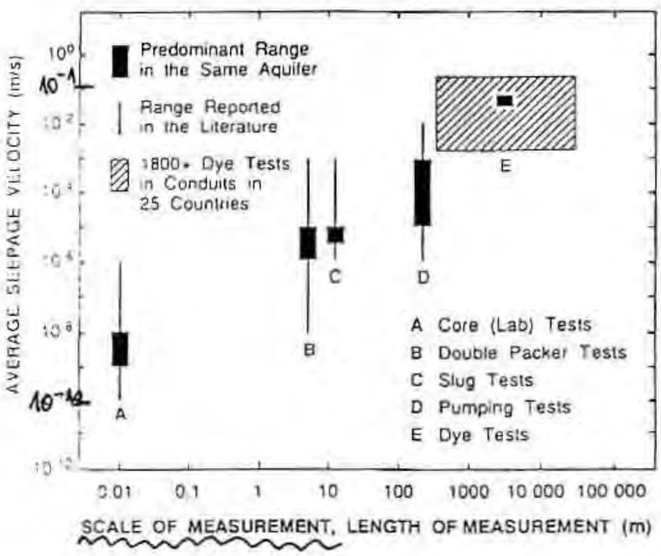

Figure 7 - Range of groundwater flow velocity determined by a variety of methods with different scale sampling (after Quinlain and others, from Benson&Yuhr,1993)

Due to the generally very pronounced anisotropy, directional conductivities may vary significantly. They have to be determined whenever a detailed study of the three-dimensional flow conditions is planned.

Flow through fractured media

Three types of conceptually different models are used to model the fluid flow within the fractured and/or karstified rocks:

1. *Equivalent continuum model*
   The fractured rock masses are assimilated to the equivalent porous media and the fluid flow within such media is modelled. Variables are defined by their average values rather than by their distribution.
2. *Discrete flow models*
   With these models, fluid flow in the discontinuities or channels is explicitly modelled. To do this, the governing flow equations are either derived for the individual discontinuities or channels or as the mass flow equations for the complete discontinuity or channel network. In the first case, the variables are defined for the individual discontinuities. In the second, the discontinuity (or channel) network variables are defined either for the individual, clearly distinguishable discontinuity (channel) sets, or stochastically, with an equivalent random probability distribution function.

3. *Double porosity models*
   Rock matrix and the discontinuity (channel) network are considered here as two distinct but overlapping continua, modelled with different but hydraulically coupled models. Rock matrix is modelled with an equivalent continuum model and the discontinuity network is generally modelled in the same way.

Initial approach to the modelling of the fluid flow in fractured and karstified rocks or discontinuity media was to assimilate them to a continuous porosity medium, with REV being the basis for homogenization. Equations were solved for the potential field and for the flow field.

The double porosity concept was added subsequently to better describe the media's behaviour - starting with two overlapping REV. Again, the equations were solved for both potential and flow field. Yet, the heterogeneity of the fractured and karstified rock masses makes in the true world the definition of an adequate REV a rather uncertain if not impossible task. Often no REV can be defined due to the limited size of the studied volume compared to the observed spacing of the discontinuity network.

Discontinuity systems models were an attempt to overcome the problems posed by the REV definition and the resulting drawbacks of the computational results of these models. Several model types were defined (Cheng-Haw-Lee,1993, Reiss,1980, Indraratna&al.,1994): *Orthogonal models (parallel, match stick, cubic), Beacher disc model, Veneziaro model, Dershowitz model and Mosaic block Tesselation models*. Solutions of the mass balance equation derived for the discontinuity system (fracture network) as a whole are making these models interesting for modelling the behaviour of the entire discontinuity system of a given fractured rock mass or, eventually, an aquifer. As previously, the resulting sets of equations are solved for the potential or for the flow field.

A recent conceptual development in the field of the discrete models are the channel flow models. They are based on the experimental observations in the low permeability fractured rocks (granites, gneiss) that the fracture fluid flow is actually concentrated to the channels at the fracture intersections (Moreno&Neretnieks,1991,1993b, Abelin&al.1994, Cacas&al.,1990) or to the narrow channels within the partly filled or otherwise tightly closed fractures. Several channel model were developed: *channelling model (noninterfering parallel channels) and channel network models.*

It seems that by the discrete flow models it is possible to avoid the necessity of a REV definition (Cacas&al.,1990) and to predict the large scale behaviour of the fractured media on the basis of its small scale definition. The latter is achievable by the direct fracture geometry measurement and the corresponding local hydraulic tests.

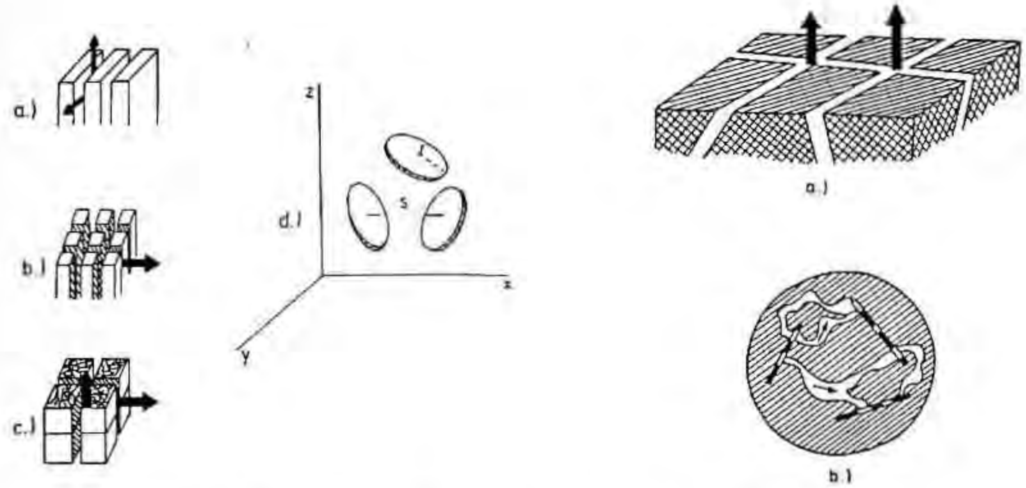

Figure 8 - Some examples of discrete flow models
Orthogonal models (left): a) parallel, b) matchstick, c) cubic; Disc models (centre): d) Beacher disc model; Channel network models (right): a) channels at fracture sections, b) channels within fractures

The discrete flow models were tested, as far as known to the author, only within the low permeable fractured rocks. They still have to be verified for the highly permeable and karstic rocks that are constituting the aquifers, interesting from the water resources point of view. For the fractured and karstified aquifers the double porosity model have been generally applied when the simple continuity model failed to furnish the adequate results.

The described conceptual models were derived to model the fluid flow within the saturated fractured media. Most of them are used also to model the fluid flow within the unsaturated fractured media. Yet, it must be pointed out at the conceptual level, that in the unsaturated fractured porous media, the fluid flow is restricted to the microfractures and avoiding macrofractures before sufficient saturation is achieved. This is best illustrated by the Figure 9. For this reason, when single continuum, double porosity or any other model is applied to the unsaturated fractured media, the saturation dependant changes in the active fracture (network) distribution and the involved fracture (network) parameters has to be taken into account. It is rather doubtful that the channel network models are the most appropriate ones for that type of job, since the channel distribution certainly reflects the distribution of the largest conduits and hence of macropores.

Finally, when modelling the fractured rock masses subjected to the strongly varying pressure fields (close to the underground or surface excavations and to the large pressure changes surrounding deep wells), the hydromechanical coupling, allowing for the stress related fracture network deformations, must be taken into account (Indraratna&al.,1994). This requires the coupling of the fracture flow models with the elasto-plastic mechanical models of the fractured rock mass.

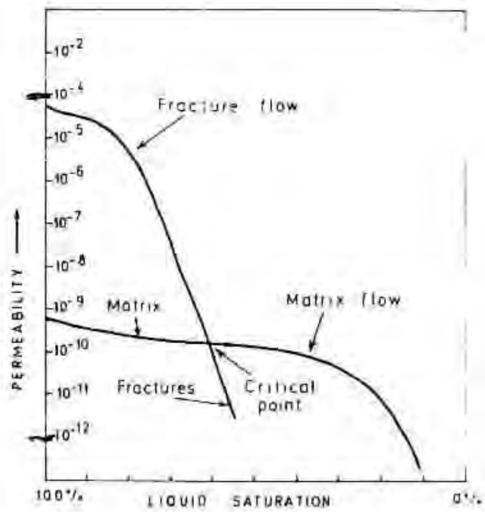

Figure 9 - Fractured media permeability under partial saturation flow conditions (after Domenico&Schwartz,1990)

Mass transport through fractured media

The same three types of conceptually different models as used to model the fluid flow through the fractured and karstified rocks are used also for modelling the mass transport through the same rocks. Here, the mass balance and flow equations are defined for a specific transported species and the equations solved for its concentration field.

The water flow rate was traditionally calculated by Darcy's law and the solute transport by the advection-dispersion equation. Darcy's law is applicable provided the flow is laminar and the media homogeneous. In a heterogeneous medium, even with a known permeability distribution, it does not determine the mean permeability and provide exact results for the local flow rate, velocity or water particle residence time variations. In the case of very broad water particle residence time distribution may be the minimum observed residence times be much shorter than calculated (Moreno&Neretnieks,1993a).

The advection-dispersion equation gives good description of the solute transport in the homogenous porous media, if the fact that the coefficient of mechanical dispersion is flow velocity dependant is observed. It is important to note that the involved dispersion coefficients have to be experimentally determined by the non-sorbing tracers.

In the highly heterogenous, fractured porous media the advection-dispersion equation does not give correct description of the solute transport, as observed in crystalline rocks by numerous authors (Matheron&deMarsily,1980, Neretnieks,1983). As observed by Moreno & Neretnieks (1993a), the flow in fractured rocks is taking place in channels and in fractures.

With a wide channel conductivity distribution (i.e. with a few extremely conductive channels), the high conductivity pathways may lead to channelling over long distances. If, given the observed distance, the channels intersect very often, a Fickian type dispersion will result and an adequate advection-dispersion model may be applied. If, on the contrary, the channels intersect very seldom, the flow situation approaches to that of parallel independent tubes. In such a case, the solute residence time will be shorter than given by the advection-dispersion model and the dispersion would be less.

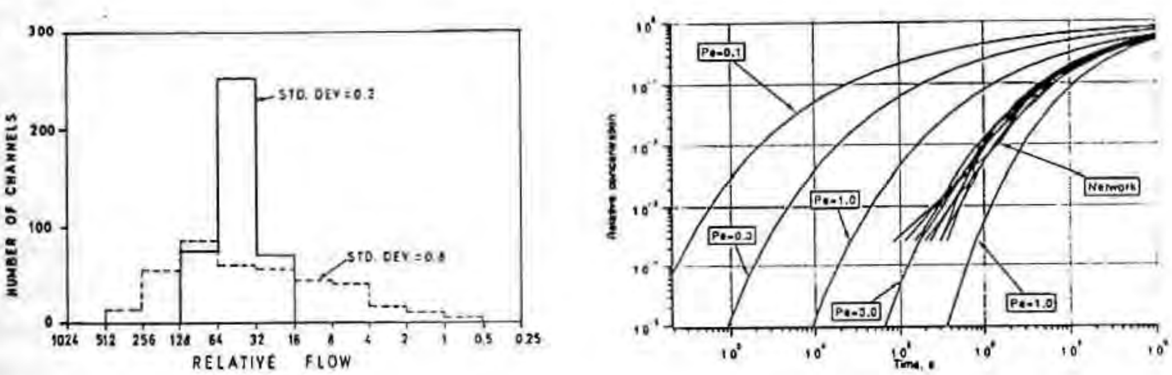

Figure 10 - Channel network (CN) model and advection-dispersion (AD) model comparison
Channel conductivity distibution effects on the relative flow (left, from Moreno&Neretnieks,1993b); Effects of continuous media's Peclet number on the AD model residence time estimates compared to the estimates of CN model with channel conductance distributin characterized by σ = 3.7 (right, from Moreno&Neretnieks,1993a).

For the solutes, which interact with the solid matter in the rock either chemically or physically, the residence time distribution can be very much different from that of the water. A porous medium can be divided into three flow domains: the mobile (gravitationally flowing) water, the stagnant water (in micropores) and the solid matter (matrix). Flow residence times of the flowing water are obtained as a quotient of flux and of effective porosity, which is in fractured and karstified rocks generally orders of magnitude smaller than the total porosity. The solutes penetrate the stagnant water by molecular diffusion. If due to small matrix blocks and long residence time all of the matrix porosity (stagnant water) is accessible, than the solutes residence time will be determined by the total porosity and will be much greater than that of the water. If due to the large blocks (long diffusion distances) and relatively short water residence time most of the matrix porosity may not be involved, than the solutes residence time will be substantially that of the water. With the intermediate cases, partial matrix penetration of the solutes will result in a large residence time distribution and break curve dispersion.

The solute retardation is proportional to the square of the flow-wetted surface which is the contact surface of the flow domain to the matrix (block) domain. The magnitude of this surface has a dominating influence on the residence times of sorbing tracers regardless of the model applied. Unfortunately, the correct determination of this surface is not easy. For flow through fractures, it can be derived from their density, length and fraction of their effective opening (generally a few percent of the fracture area). For flow through channels, it can be deduced from the data on channel lengths and widths.

According to Moreno and Neretnieks (1993a) the channel network model better describes the flow through the fractured rocks as either the channelling or the advection-dispersion model, provided the data on channel water conductivity distribution are known from hydraulic tests. Similar are the conclusions of Cacas &al. (1990). These models were applied to the rock volumes of the order of the corresponding REV, which are already comparable to that of the ordinary aquifers - up to 10^6 m^3 as reported for Cacas&al., up to $1x10^7$ m^3 as estimated for the Moreno&Neretnieks case. For bigger fractured media volumes, even when the appropriate data available, the computer memory requirements may become prohibitive (Cacas&al.,1990) and the advection-dispersion model will still have to be used. Conclusions of these authors must therefore be carefully examined, bearing in mind, however, the low or even very low permeability of the studied rocks.

For the fractured porous media volumes bigger than the REV, when using the advection-dispersion model, it is important to note that the data on hydrodynamic dispersion must be obtained by the non-sorbing tracer test.

From our discussion it follows, that the flow and mass transport through such porous media are scale dependant (Cheh-Haw-Lee,1993, Moreno&Neretnieks,1991, 1993b, Abelin&al.1994, Cacas&al.,1990). For flow distances that are orders of magnitude bigger than the adequate REV, the advection-dispersion model looks appropriate. For long flow distances, equalling from one tenth to some orders of REV, the fracture or channel network flow models seem adequate. For short distance flow, shorter than some orders of REV, the channel flow model seems the most suitable. From the above statements it follows that the flow and transport behaviour are relative scale and not absolute scale dependant. The appropriate flow and transport model selection will depend on the adequate description of the intrinsic structural and flow features of the porous media.

To give an insight into the nature of fluid flow, of mass transport and of particle sorption, we have in our past discussion concentrated to the pollutants that perfectly dissolve and mix (dilute) in the water, and which, by doing so, do not change the water's flow properties and its water-rock interactions. Even here, we had to differentiate between the sorbing and the non-sorbing species. Actually, several types of vastly different fluid flow to pollutant mass transport relations exist, giving birth to different types of pollution propagation. We can differentiate between the following pollutant mass transport types:

a) Soluble and well mixing (diluting) species that do not change water flow and rock wettability properties; advection, dispersion, diffusion and retardation (sorption, decay) mechanisms are involved; examples: radioactive tracers, various salts
b) Soluble and well mixing (diluting) species that change water flow and rock wettability properties; advection, dispersion, diffusion mechanisms are involved but little retardation; example: detergents and other surfactants
c) Soluble, but poorly mixing cases due to a change in the water density and flow properties; advection, dispersion, diffusion and retardation (cooling) mechanisms are involved; examples: hot water, salty marine water
d) Nonsoluble but well mixing species that do not change water flow and rock wettability properties; advection, dispersion, and retardation (dying, decay) mechanisms are involved but no diffusion; examples: bacteria, viruses, colloids, suspended matter
e) Poorly soluble but nonmixing fluids creating multiphase flow conditions; advection, dispersion and retardation (sorption, oxidation, decay) are active within the pollutant phase flow domain, solution at the phase boundary and advection, dispersion, diffusion and retardation of dissolved species in the water flow domain; examples: various non-aqueous phase liquids (NAPL) with light (LNAPL) and dense (DNAPL) varieties

Mass transport mechanisms with respect to the water flow are for the above enumerated types a) through d) practically identical - they are all adhering to the single phase mixing flow conditions of which our past discussion was representative. Type b) is only changing the water flow properties, which may lead in better channelling and less dispersion. With the type c) poor mixing becomes important with low gradient and velocity flows, but is very obvious with hot springs in fractured aquifers. Finally, concerning the type d), it is obvious that suspended matter in general (bacteria and viruses involved) can not be moved by diffusion. We tried to show that also the retardation effects may differ characteristically between the enumerated types of pollution propagation. Obviously, we did not intend to enumerate all the possible retardation mechanisms. which may differ very much from species to species and from case to case.

The above type e) represents in fact quite different flow and mass transport conditions from the previously observed. We are illustrating this type of no-mixing flow conditions on the Figure 11 with a case where the polluting fluid (LNAPL) is flowing as a lens close to the aquifers water table. The movement of the polluting fluid is governed by the same laws and influenced by the same fractured porous media properties as previously elaborated for the single phase fluid flow. However, as its density, viscosity, relative rock wettability and saturation are different from that of the aquifer's water, its flowing velocity is very different from that of the adjacent water. Generally, such polluting fluid bodies are moving relatively slowly. Due to this, the water pollution resulting from the solution of various species at the water - polluting fluid interface is generally the main pollution mechanism. The resulting type of mass transfer is then the already discussed type a) of the mixing flow conditions.

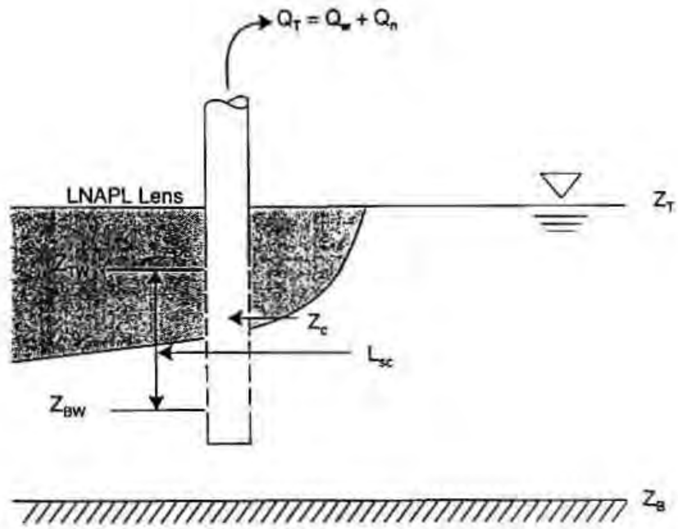

Figure 11 - Pollution of an aquifer with a non-mixing polluting fluid
Case of a LNAPL pollution (from Huyakorn&al.,1993b)

As far as the pollutant transport is considered, the unsaturate flow domain has many particular features. The fluid flow is mostly vertical, the pore saturation is seldom complete and therefore the flow retarded, capillarity and water retention play important role, as do the sorption processes, bacterial activity and oxidation (especially in the soil horizon). All this is resulting in the well observed and known fact that most of pollution deactivation is taking place in the unsaturated zone. This fact is qualitatively illustrated by the Figure 12.

The mass transport in the unsaturated fractured media, is influenced by the specifics of the unsaturated flow in such media and by their mass transport related properties. Pore surface area and, especially, the flow-wetted area of such rocks are much smaller than of the rocks with intergranular porosity. Pollutant fixation will therefore be much smaller. Due to the nature of such rocks especially when carbonate rocks are considered, the surface covering soils are thinner and the infiltration flows are faster, all this giving less time for pollutant decay. As pointed out already when discussing the unsaturated flow, the matrix porosity flow is preponderant within the unsaturated zone. Therefore, a greater matrix porosity within the unsaturated zone will lead to a greater pollutant fixation potential. With the fractured and karstified rocks, weathering can certainly provide some additional matrix porosity within the unsaturated zone - which is a specifics, compared to the rocks with intergranular porosity.

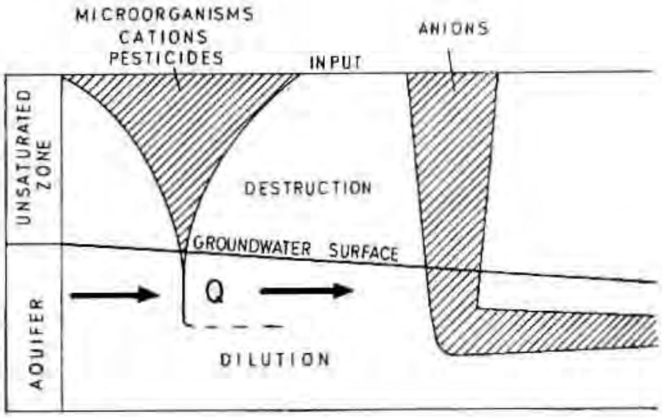

Figure 12 - Effect of the unsaturated zone on the pollutant transport (after Castany,1982)

POLLUTION CONTROL IN FRACTURED MEDIA

Already when discussing the principles of groundwater pollution control, we have pointed out that two different cases are present: 1) groundwater with little or no resource value, but possible transmitter of pollution to other groundwater and surface water bodies and the environment, and 2) aquifers of actual or potential water resources value.

Impervious or little pervious (semipervious) rock massifs are generally involved when dealing with the first of the above two cases. The pollution control and the corresponding protection measures in fractured media do not differ from what is applied in the case of low permeability intergranular media. With fractured media, however, the water flow and the pollutant transport have to be modelled according to the principles, discussed in previous chapters. Also field parameter determination, monitoring and containment measures have to take into account the specific nature of these media.

Aquifers constituting actual or potential water resources represent well permeable or highly permeable fractured and karstified rocks. Heterogeneity and anisotropy of these rocks are even more evident than with the low permeability rocks. These are the media with pronounced fracture and channel porosities. Hydraulic conductivity of these rocks is several orders of magnitude greater than that of the impervious and semipervious rocks, studied for the waste repository purposes. Field parameter determination and groundwater monitoring must take into account not only the aquifer's intrinsic characteristics and regional variability, but also the high speed of the water movement. The same is true for pollution containment measures and other intervention measures directed at pollution abatement.

Due to the quick water flow and to the relatively poor rock matrix pollutant retention capacity, the movement of pollutants is generally much faster than in the case of the aquifers with intergranular porosity. After a pollutant has penetrated the aquifer the intervention is often impossible and its monitoring may be impossible as well. For these reasons, the properly designed protection zones are the most important practical water resources protection measures for such aquifers.

The previously discussed general principles of the protection zone design, have to be slightly modified to meet the specifics of fractured and karstified aquifers. The following criteria must be used define the protection zones:

1) hydrographic criteria (surface flow divides),
2) hydrogeologic criteria (hydrogeological structure - spatial distribution and extension of pervious and impervious rocks; related infiltration and high flow areas),
3) hydrodynamic criteria (groundwater divides, flow velocity from the potential pollutant inflow locality to the protected catchment, flow related residence time and dilution of the pollutant, pollutant retardation),
4) intervention criteria (possibility, type, delay, feasibility)

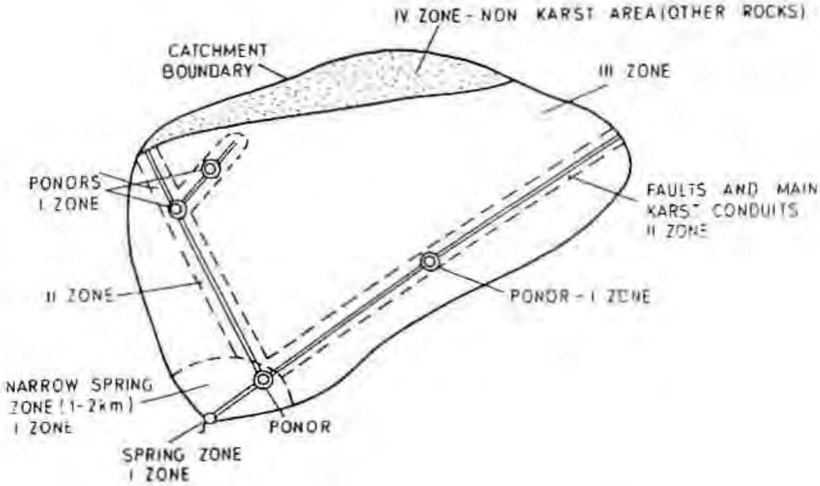

Figure 13 - Karst aquifer protection zones in an alpine area

The just exposed criteria are illustrated by the Figure 13 showing the karst aquifer protection zone design principles. A practical case is shown on the Figure 14.

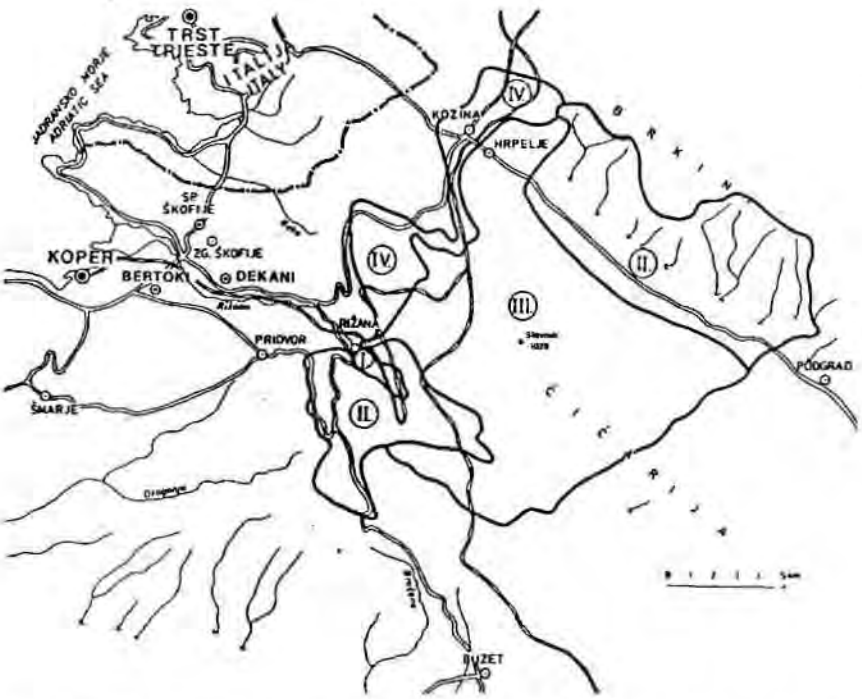

Figure 14 - Groundwater protection zones of the Rižana karst spring (after Krivic&al.,1989)

The studies of the propagation of pollutant species, belonging to the different pollutant mass transport types, have shown that the fractured and, especially, the karstified aquifers are particularly sensible to the polluting germs (Motyka&al., 1994, Krešić&al.,1992, Thorn&Coxon,1992). It was found (Janež,1989) that in many smaller and medium sized Slovene alpine karst aquifers, the high flow (sometimes even the low flow) germs residence times do not meet the requirements of the previously stated German, Slovene or even Swiss standards. The idea of defining the protection zones in function of the aquifer's local vulnerability was therefore advanced for such cases. Intervention times, based on the local pollution monitoring facilities and intervention capabilities, were suggested as the protection zones defining criteria. This has proved to be an efficient approach in such cases.

Other interesting aspects of pollution propagation of NAPL in fractured and karstified aquifers - linked to the deep water table conditions - were also experienced in Slovenia. Pollution from two point source oil spils moved across the unsaturated zone much slower than expected. In the Žužemberk case, it finally reached the saturated zone, but in very limited amount. In the oil spil within the catchment area of the Rižana karst spring case, no influence of the spill on the saturated zone flow was so far observed. This proves that the role of the thick unsaturated zone in the fractured and karst aquifers is still to be elucidated and the results integrated into the criteria for protection zone definition.

VULNERABILITY

Catastrophic	Great	Medium	Low
no time to prevent the pollutant from entering the water supply system	less than 12 h to prevent the pollutant from entering the water supply system	over 12 h to prevent the pollutant from entering the water supply system	more than 12 h to prevent the pollutant from entering the aquifer
1. Zone Zone of immediate protection	2. Zone Zone of inner protection	3. Zone Zone of outer protection	4. Zone Zone of restricted protection

PROTECTION ZONES

Figure 15 - Aquifer vulnerability integrated in protection zoning (after Janež,1989)

As the end of this discussion on the protection zone definition and design, let me stress that the protection zone design is primarily an engineering and not a scientific or a research problem. For this reason it is vital to take into account the principle of lowest overall protection and therefore resource cost. When the extension of a protection zone over the hydrogeologically greatest possible potential pollutant inflow area and the resulting restrictions of its use do not collide with the economic interests of other users of this area - then it is economically useless to invest into the research related to the definition of the given protection zone. In such a case it is best to decide on the highest possible protection level of the given area. The studies oriented towards lowering the resource protection level or down-sizing the protection zones must be paid by the subsequent users of this area. This has been the concept applied several times in the Slovene praxis.

CONCLUSION

Water quality is of great interest in any development or management of water resources. With the increased demand for water it is becoming the limiting factor in the development and use of water resources. Groundwater pollution control, involving pollution reduction and prevention and anti-pollution protection can be regarded as a general environmental protection, or as a water resources protection.

Hydraulic conductivity of fractured and karstified rocks, called also fractured media, depends primarily on the fissure, fracture and channel (karst channel) network characteristics. For most rocks it varies over several orders of magnitude.

Conceptually different types of models are being used to model the fluid flow and pollutant transport within the fractured and karstified rocks. To be able to back the pollution control in fractured and in karstified rocks by mathematical modelling, the nature of these media and of the corresponding flow and mass transport must be adequately described.

Depending on the scope of the study, two basic approaches will continue to coexist in the modelling the flow and mass transport phenomena in the fractured and karstified rocks. For small scale technical and groundwater pollution problems (such as waste repository studies) the discrete flow models will be more and more applied. For regional groundwater flow problems, related to the aquifer pollution control, the advection-dispersion model and the related double porosity models will further be used. Their use should be backed by proper internal aquifer regionalization, based on the respective REV and flow parameters definition. The appropriate structural and hydrogeological methods should be used for the purpose.

There will always be cases where the conceptual models and practical engineering approaches will have to substitute the mathematical modelling and where the intuitive solutions will have to overcome the lack of data. The general knowledge provided by the research of the flow and transport phenomena will help to improve this type of solutions and actions.

At the current state of pollution control of water resources, the protection zones represent the main legal protective and preventive measure. Whereas for the aquifers with intergranular porosity these zones are generally quantitatively defined, it is not so for the protection zones in fractured and, especially, karstified aquifers. Here, most of the protection zone design is still done on the intuitive and qualitative bases. There is strong evidence that due to the extensive research effort in the fields of fractured aquifer description and fracture and channel flow modelling the situation might within short improve considerably.

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